I/Q Regeneration Algorithm for Direct Conversion Receiver Using 5-Port Junction

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Abstract— **We introduce a reliable I/Q regeneration algorithm for digital video broadcasting system (DVB-S) using a 5-port junction direct conversion receiver. The DVB-S uses two modulation schemes; QPSK and 8PSK. We propose two cost functions for each modulation scheme. The proposed algorithm utilizes the charateristic of the modulated symbol, so it simplifies the phase-offset compensation problem with low complexity. Simulation results show that bit error rate (BER) of the proposed scheme agrees very well with the theoretical BER for QPSK and 8PSK.**

I. Introduction

The increasing demand for digital communications needs high speed and multimedia transmission. Besides the availability of low-cost and low-power user terminals is also required. To achieve high data rate and reduce the cost and the power of the user terminals, it has been focused on replacing a superheterodyne receiver structure to a homodyne; direct conversion receiver structure.

To overcome the limits of the conventional direct conversion receiver, a new direct receiver with a 5-port junction has been proposed [1]. Due to the structure of the 5-port junction, however, the receiver needs special digital signal processing techniques in the baseband. So far the method using singular value decomposition [2] and the scheme applying the Gram-Schmidt orthogonalization [3] have been proposed. Both schemes [2] and [3], however, must compensate the phase offset of the regenerated I/Q signals and require high computational complexity. In order to solve the above problems and to obtain the reliable performance, we propose an I/Q regeneration algorithm in the 5-port direct conversion receiver for digital video broadcasting services. Our scheme is based on the constant modulus algorithm (CMA) [5] and utilizes the charateristic of the modulated symbols.

The paper is organized as follows: Section II introduces the system model of the 5-port junction direct conversion receiver. In Section III, the proposed I/Q regeneration algorithms are derived for QPSK and 8PSK. The performance of our I/Q regeneration methods is evaluated by computer simulation, and the results are presented in Section IV. Finally, we draw a brief conclusion of this paper in Section V.

II. 5-port junction direct conversion receiver

The 5-port direct conversion receiver consists of an RF circuit with 5-port junction and a baseband. Figure 1 shows a block diagram of the 5-port direct conversion receiver [2]. It takes two input signals; RF signal and LO signal. The RF signal can be expressed as

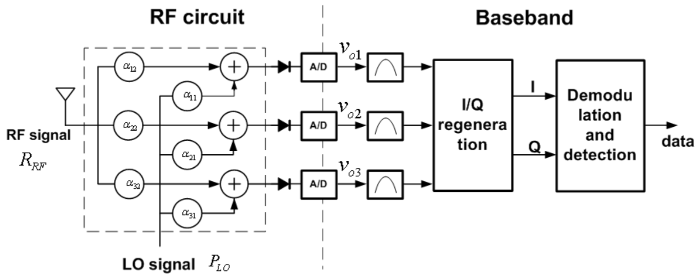

Fig. 1. Block diagram of the 5-port junction direct conversion receiver

$$R_{RF}(t) = A_{RF}(m(t) + w(t))\, exp\,(j2\pi f_{RF}t), \qquad (1)$$

where $m(t)$ is the message signal, f_{RF} is the carrier frequency, $w(t)$ is AWGN and A_{RF} is the amplitude of the RF signal. For the quadrature modulation scheme, the message signal $m(t)$ is composed of an I and a Q component.

$$m(t) = m_I(t) + j\, m_Q(t), \qquad (2)$$

where

$$m_I(t) = \sum_k I_k h(t - kT_s)$$
$$m_Q(t) = \sum_k Q_k h(t - kT_s).$$

In the above equation, I_k and Q_k represent the I and Q component, respectively; T_s is the symbol period; $h(t)$ is the impulse response of the squared root raised-cosine (SQRC) filter.

In (1), $w(t)$ also can be expressed with the I and Q component.:

$$w(t) = w_I(t) + j\, w_Q(t). \qquad (3)$$

Another input of the 5-port direct conversion receiver input, the LO signal is

$$P_{LO}(t) = A_{LO}\, exp\,(\, j2\pi f_{LO}t + \theta\,). \qquad (4)$$

In (4), A_{LO} represents the amplitude of the LO signal; f_{LO} represents the frequency of the LO signal; θ is the phase difference between the RF and LO signals. In this paper, we assume that $f_{RF} = f_{LO}$.

For brevity of notation, we define:

$$\begin{aligned} c(t) &= c_I(t) + j\, c_Q(t) \\ c_I(t) &= m_I(t) + w_I(t) \\ c_Q(t) &= m_Q(t) + w_Q(t). \end{aligned}$$

The two inputs defined above are linearly mixed throughout the 5-port junction and become three outputs, $v_i(t)$'s.

$$v_i(t) = \alpha_{i1}\, P_{LO}(t) + \alpha_{i2}\, R_{RF}(t), \quad i \in \{1,2,3\}. \quad (5)$$

where α_{ij}'s are complex-valued parameters and are decided by a structure of the 5-port junction. Then, $v_i(t)$'s are fed into the power-detector, which consists of a diode and a low-pass filter. The three outputs of the power-detector can be expressed as

$$\begin{aligned} v_{oi}(t) &= S\left(v_i(t)\right)^2 \\ &= A|\alpha_{i1}|^2 + B|\alpha_{i2}|^2(\, c_I^2(t) + c_Q^2(t)\,) \\ &+ C|\alpha_{i1}||\alpha_{i2}|(\, c_I(t)\cos(\gamma_i) + c_Q(t)\sin(\gamma_i)), \\ & i \in \{1,2,3\}. \end{aligned} \quad (6)$$

where S, A, B and C are constants and

$$\gamma_i = \angle\, \alpha_{i2} - (\angle\, \alpha_{i1} + \theta),\ i \in \{1,2,3\}.$$

From (6) each output is composed of three terms. The first term represents the self-mixing of the LO signal and forms the DC-offset. The second is the self-mixing of the message signal. The last represents the mixing between the message and LO signals, which contains the down-converted message signal. Thus the special digital signal processing technique is required to obtain the message signal from the last term in (6) for the 5-port direct conversion receiver.

After removing the DC-offset, three outputs from the power-detector are passed through the A/D converter with sampling period, τ_s and digitized as

$$\widetilde{v}_{oi}(n\tau_s) = L_i v_a(n\tau_s) + a_i c_I(n\tau_s) + b_i c_Q(n\tau_s), \quad (7)$$

where

$$\begin{aligned} L_i &= SB|\alpha_{i2}|^2,\ N_i = SC|\alpha_{i1}||\alpha_{i2}| \\ a_i &= N_i cos(\gamma_i), \\ b_i &= N_i sin(\gamma_i),\ i \in \{1,2,3\}. \end{aligned}$$

In (7), v_{oi} is the amplitude modulation (AM) noise [2]. With the matched filter using the SQRC filter outputs of the 5-port direct conversion receiver $x_i(n)$'s can be obtained from $\widetilde{v}_{oi}(n)$'s as:

$$\begin{aligned} x_i(n) &= h(n) \odot \widetilde{v}_{oi}(n\tau_s) \\ &= N_i\left(I(n)\cos(\gamma_i) + Q(n)\sin(\gamma_i)\right) + L_i U(n), \\ & i \in \{1,2,3\}. \end{aligned} \quad (8)$$

where $I(n) = h(n) \odot c_I(n\tau_s)$, $Q(n) = h(n) \odot c_Q(n\tau_s)$, $U(n) = h(n) \odot v_a(n\tau_s)$.

Then (8) can be expressed in matrix form as

$$\mathbf{x(n)} = \mathbf{Fs(n)}, \quad (9)$$

where

$$\mathbf{x(n)} = \begin{bmatrix} x_1(n) \\ x_2(n) \\ x_3(n) \end{bmatrix},\ \mathbf{s(n)} = \begin{bmatrix} I(n) \\ Q(n) \\ U(n) \end{bmatrix}$$

$$\mathbf{F} = \begin{bmatrix} N_1\cos(\gamma_1) & N_1\sin(\gamma_1) & L_1 \\ N_2\cos(\gamma_2) & N_2\sin(\gamma_2) & L_2 \\ N_3\cos(\gamma_3) & N_3\sin(\gamma_3) & L_3 \end{bmatrix}.$$

From (9) the goal of the study is to find a matrix consisting of two vectors: $\mathbf{W} = [\mathbf{w_I}, \mathbf{w_Q}]$ that satisfies

$$\mathbf{y(n)} = \begin{bmatrix} I(n) \\ Q(n) \end{bmatrix} = \mathbf{W^T x(n)}. \quad (10)$$

III. Proposed I/Q regeneration algorithms

The conventional I/Q regeneration algorithms are using singular value decomposition [2] and based on the Gram-Schmidt orthogonalization [3]. In DVB-S which adopts two modulation schemes; QPSK and 8PSK, the phase rotation occurs at the regenerated symbols by the conventional algorithms and the phase offset compensation should be carried out. The phase offset is mainly from local oscillator mismatch between the transmitter and the receiver ends as well as the one caused from the algorithms themselves. To overcome the phase offset problem, we propose I/Q regeneration algorithms for QPSK and 8PSK based on the CMA [5] exploiting the charateristic of modulated symbols.

A. Proposed I/Q regeneration algorithm for QPSK

Proposed I/Q regeneration algorithm for QPSK starts from the charateristic that for every QPSK modulated symbol, $\cos^2\theta$ and $\sin^2\theta$ are equal. In other words,

$$\cos^2\theta = \sin^2\theta. \quad (11)$$

If the phase offset occurs at modulated symbols, $\cos^2\theta$ and $\sin^2\theta$ is not equal. Using this charateristic, we can define error functions as

$$\begin{aligned} e_1(n) &\triangleq \mathbf{y^T}(n)\mathbf{y}(n) - A = I^2(n) + Q^2(n) - A, \\ e_2(n) &\triangleq \cos^2\theta - \sin^2\theta = \frac{I^2(n) - Q^2(n)}{I^2(n) + Q^2(n)}. \end{aligned} \quad (12)$$

In (12), $e_1(n)$ is an error function adopted from the CMA. Since the proposed error function $e_2(n)$ uses the charateristic above, it makes the phase offset compensation problem much easier than that of the conventional methods [2] and [3].

Using the error functions above we can define the cost function as

$$\begin{aligned} J(n) &\triangleq J_1(n) + J_2(n) \\ &= E\left[e_1^2(n)\right] + E\left[e_2^2(n)\right] \end{aligned} \quad (13)$$

With the stochastic gradient method, the update equation of the two vectors $\mathbf{W} = [\mathbf{w_I}, \mathbf{w_Q}]$ which minimize the cost function $J(n)$ can be expressed as

$$\begin{aligned} \mathbf{w}_I(n+1) &= \mathbf{w}_I(n) - \mu \cdot \nabla_{\mathbf{w}_I} J(n), \\ \mathbf{w}_Q(n+1) &= \mathbf{w}_Q(n) - \mu \cdot \nabla_{\mathbf{w}_Q} J(n) \end{aligned} \quad (14)$$

In (14), $\nabla_{\mathbf{w}_I} J(n)$ is represented as follows:

$$\begin{aligned}\nabla_{\mathbf{w_I}} J(n) &= \frac{\partial}{\partial \mathbf{w_I}} J(n) \\ &= \frac{\partial}{\partial I} J(n) \cdot \frac{\partial I}{\partial \mathbf{w_I}} \\ &= \frac{\partial}{\partial I} \left\{ J_1(n) + J_2(n) \right\} \cdot \frac{\partial I}{\partial \mathbf{w_I}}.\end{aligned} \tag{15}$$

In the above equation,

$$\begin{aligned}\frac{\partial}{\partial I} J_1(n) &= \frac{\partial}{\partial I} \left\{ E\left[\left(I^2(n) + Q^2(n) - A \right)^2 \right] \right\} \\ &= 4\left(I^2(n) + Q^2(n) - A \right) \cdot I(n) \\ &= 4 \cdot e_1(n) \cdot I(n).\end{aligned} \tag{16}$$

Before formulating $\frac{\partial}{\partial I} J_2(n)$, we assume that the denominator $E\left[I^2(n) + Q^2(n)\right]$ of the $J_2(n)$ is constant at the steady-state of the matrix $\mathbf{W}$. Then

$$\begin{aligned}\frac{\partial}{\partial I} J_2(n) &= \frac{\partial}{\partial I} \left\{ E\left[\left(\frac{I^2(n) - Q^2(n)}{I^2(n) + Q^2(n)} \right)^2 \right] \right\} \\ &\cong 4\left(\frac{I^2(n) - Q^2(n)}{I^2(n) + Q^2(n)} \right) \cdot I(n) \\ &= 4 \cdot e_2(n) \cdot I(n).\end{aligned} \tag{17}$$

Thus

$$\begin{aligned}\nabla_{\mathbf{w_I}} J(n) &= \frac{\partial}{\partial \mathbf{w_I}} J(n) \\ &= 4\left(e_1(n) + e_2(n) \right) \cdot I(n) \cdot \mathbf{x(n)}.\end{aligned} \tag{18}$$

With the same way for $\nabla_{\mathbf{w}_I} J(n)$, $\nabla_{\mathbf{w}_Q} J(n)$ is as follows:

$$\begin{aligned}\nabla_{\mathbf{w}_Q} J(n) &= \frac{\partial}{\partial \mathbf{w}_Q} J(n) \\ &= 4\left(e_1(n) + e_2(n) \right) \cdot Q(n) \cdot \mathbf{x(n)}.\end{aligned} \tag{19}$$

B. Proposed I/Q regeneration algorithm for 8PSK

With the same analysis as the case for the QPSK, the proposed algorithm utilizes the charateristic of the 8PSK modulated symbols. For 8PSK modulation scheme, the square of the difference between $\cos^2\theta$ and $\sin^2\theta$ are equal to $\frac{1}{2}$ at every modulated symbol.

$$\left(\cos^2\theta - \sin^2\theta \right)^2 = \frac{1}{2}. \tag{20}$$

With the same sense to QPSK modulation case, we can define the error functions as

$$\begin{aligned}e_1(n) &\triangleq \mathbf{y}^{\mathbf{T}}(n)\mathbf{y}(n) - A = I^2(n) + Q^2(n) - A, \\ e_2(n) &\triangleq \left(\cos^2\theta - \sin^2\theta \right)^2 - \frac{1}{2} = \left(\frac{I^2(n) - Q^2(n)}{I^2(n) + Q^2(n)} \right)^2 - \frac{1}{2}.\end{aligned} \tag{21}$$

The cost function for the above error functions will be defined as

$$\begin{aligned}J(n) &\triangleq J_1(n) + J_2(n) \\ &= E\left[\left(e_1(n)^2 \right) \right] + E\left[\left(e_2(n)^2 \right) \right]\end{aligned} \tag{22}$$

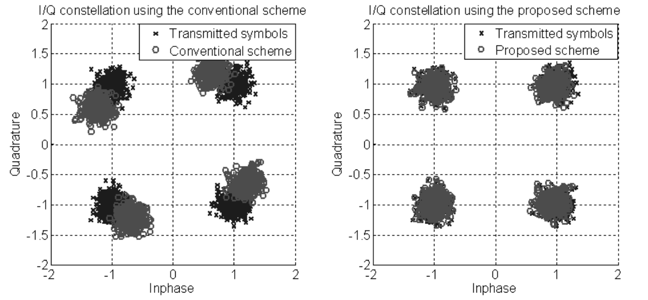

Fig. 2. Constellation of the transmitted and regenerated symbols for QPSK

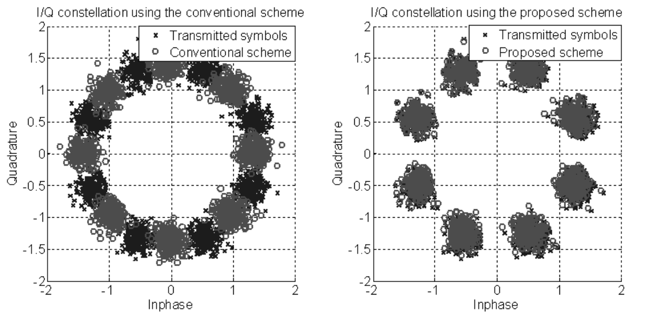

Fig. 3. Constellation of the transmitted and regenerated symbols for 8PSK

With stochastic gradient method, the update equation of the two vectors, $\mathbf{W} = [\mathbf{w}_I, \mathbf{w}_Q]$ can be obtained as

$$\begin{aligned}\mathbf{w}_I(n+1) &= \mathbf{w}_I(n) - \mu \cdot \nabla_{\mathbf{w}_I} J(n), \\ \mathbf{w}_Q(n+1) &= \mathbf{w}_Q(n) - \mu \cdot \nabla_{\mathbf{w}_Q} J(n).\end{aligned} \tag{23}$$

In the above equation, $\nabla_{\mathbf{w}_I} J(n)$ and $\nabla_{\mathbf{w}_Q} J(n)$ are obtained as follows:

$$\begin{aligned}\nabla_{\mathbf{w}_I} J(n) &= \frac{\partial}{\partial \mathbf{w}_I} J(n) \\ &= 4\left\{ e_1(n) + 2 \cdot e_2(n) \cdot \frac{I^2(n) - Q^2(n)}{I^2(n) + Q^2(n)} \right\} \cdot I(n) \cdot \mathbf{x(n)},\end{aligned} \tag{24}$$

$$\begin{aligned}\nabla_{\mathbf{w}_Q} J(n) &= \frac{\partial}{\partial \mathbf{w}_Q} J(n) \\ &= 4\left\{ e_1(n) + 2 \cdot e_2(n) \cdot \frac{I^2(n) - Q^2(n)}{I^2(n) + Q^2(n)} \right\} \cdot Q(n) \cdot \mathbf{x(n)},\end{aligned} \tag{25}$$

IV. Simulation Results

In this section, we demonstrate the performance of our I/Q regeneration algorithm on signal constellation and system BER performance under AWGN channel. We assume the perfect symbol timing synchronization and no frequency offset. The roll-off factor of the SQRC filter is 0.35. With the rule of thumb, the step-size μ are set to 0.002 and 0.003 for QPSK and 8PSK respectively. The initial vale of $\mathbf{W}$ is set to as

$$\boldsymbol{W} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}^{\mathbf{T}}.$$

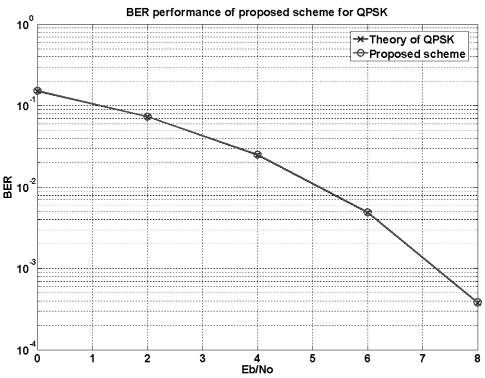

Fig. 4. BER performance of the proposed scheme for QPSK

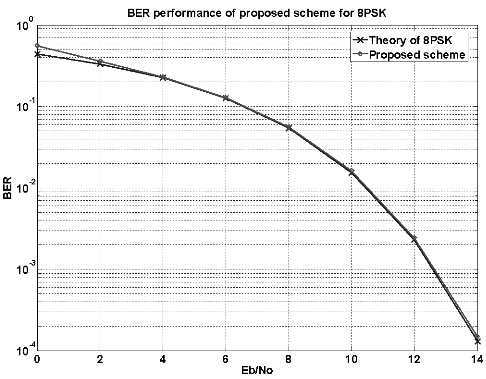

Fig. 5. BER performance of the proposed scheme for 8PSK

Figures 2 and 3 are the constellations of transmitted symbols and the regenerated symbols using the convetional scheme and our algorithm for QPSK and 8PSK at 15 dB. From the constellation, it can be seen that the constellations of regenerated symbols using the proposed algorithms are fixed to that of the transmitted symbols with the help of the error function $e_2(n)$ in (12) and (21). However since the proposed algorithm is based on the blind signal processing, there exists the following phase ambiguities between the transmitted symbols and the regenerated symbols:

$$QPSK : \left\{0, \frac{1}{2}\pi, \pi, \frac{3}{2}\pi\right\},$$

$$8PSK : \left\{0, \frac{1}{4}\pi, \frac{1}{2}\pi, \frac{3}{4}\pi, \pi, \frac{5}{4}\pi, \frac{6}{4}\pi, \frac{7}{4}\pi\right\}.$$

The reason of the phase ambiguity is that the proposed cost functions have several local minima. In other words, even if the regenerated symbols have the phase ambiguity, they satisfy the proposed cost functions. However, using a few known symbols it can be cleared easily with low complexity compared with the conventional phase offset compensation schemes.

Figure 4 and 5 illustrate the BER performance of the direct conversion receiver using the proposed algorithm for QPSK and 8PSK. Since the techniques to remove the phase ambiguity depend on the system design, it is assumed that the phase ambiguities are perfectly cleared. From the figure, it can be seen that the BER performance using the proposed scheme agrees very well with the theoretical performance curve. The reason of the small performance degradation is due to the steady-state error of $\mathbf{W} = [\mathbf{w}_I, \mathbf{w}_Q]$. However, it can be solved by selecting appropriate initial value and the step size.

V. Conclusions

In this paper, we have proposed the I/Q regeneration algorithm for the DVB system using the 5-port junction direct conversion receiver. Since the proposed scheme exploits the charateristic of the QPSK and 8PSK modulated symbols, the constellation of the regenerated symbols is fixed to that of transmitted symbols. Although the phase ambiguity exists at the regenerated I/Q symbols, it can be easily removed with a few known symbols. In other words, the proposed algorithm simplifies the phase offset compensation problem and reduces the hardware complexity. We have shown that the performance of the proposed I/Q regeneration algorithms agrees very well with the theoretical BER for QPSK and 8PSK.

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